Improved Transformer Duality Model for Geomagnetically Induced Currents

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Abstract

A lumped element transformer tank model has been developed for evaluating the power dissipation in the tank and flux distribution in the transformer when it is subjected to a DC current in the neutral.

FEM simulations are performed to assist in developing a per-phase magnetically separated transformer tank model that takes into account currents induced in the tank.

The tank is modeled with a reluctance network that is transformed to its electrical equivalent using the duality principle.

The electrical equivalent lumped element transformer models are simulated using circuit simulation software. The models are subjected to a DC current in the neutral in the circuit simulation software. For the T-core transformer the tank is saturated at comparably low DC currents in the neutral. The power dissipation in the tank for DC currents in the neutral is found to be low compared to other loss components. However, the proposed per-phase models show a higher power dissipation in the tank compared to the zero-sequence tank model.

Lumped element modeling provides an efficient alternative to FEM simulations for simulating the electromagnetic behavior of the power transformer when subjected to DC currents in the neutral.
**Sammanfattning**

En modell, baserad på diskreta element, har utvecklats för transformatorlådan för att utvärdera effektutveckling i transformatorlådan samt flödesdistribution i transformatorn när den utsätts för en DC-ström i nollan.

FEM-simuleringar utförs för att assistera i utvecklandet av en per-fas magnetiskt separerad lådmodell som tar hänsyn till inducerade strömmar i lådan.

Lådmodellen modelleras med ett reluktansnätverk som sedan, baserat på dualitetsprincipen, transformeras till en elektriskt ekvivalent modell.


Modellering med diskreta element tillhandahåller ett effektivt alternativ till FEM-simuleringar för att studera transformatorns elektromagnetiska beteende vid DC-strömmar i nollan.
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Chapter 1

Introduction

1.1 Background

Today, we are highly dependent on the supply of electricity. Even short interruptions may cause substantial losses for both supplier and customer. At the same time, many of today’s power systems are very exposed to the effects of space weather. One such effect is geomagnetically induced currents. These currents could possibly damage power systems and power transformers in particular. Due to the long lead-time of large power transformers, a large solar storm could cause great harm to the grid. It is not surprising that grid owners and power transformer producers want to investigate this issue further.

During a GIC event, the behaviour of a transformer will be a combination of a positive- and zero-sequence behaviour. For the purpose of investigating the possible effects of a GIC event, a detailed model of the transformer is needed. While a transformer’s positive- and negative sequence impedance is determined mostly by the core, the zero sequence impedance will be influenced by the transformer tank and other off-core paths. The tank acts as both a flux path and a fictive winding during certain circumstances.

1.2 Geomagnetically induced currents

Geomagnetically induced currents, or GICs, are, as the name suggests, currents induced by geomagnetic activity. Coronal Mass Ejections (CMEs) eject charged particles that reach the ionosphere of the earth. When the charged particles reach the ionosphere, they divert and form electrojets. Electrojets are current layers in the ionosphere. The electrojets generate a surrounding magnetic field that couples to loops on earth, inducing currents in overhead lines. For Y-connected power transformers, the induced current will usually flow through the HV winding and through the neutral, since the HV side together with overhead lines form longer loops for the magnetic flux, from the electrojets, to couple with.

An illustration is given in figure 1.1.
Figure 1.1: This figure shows an illustration of a power network with a power plant, two transformers and a grid. Figure adapted from [1].

GIC amplitudes up to a few hundred amperes have been recorded historically [2].

An illustration of a typical GIC spectrum during a GIC event is depicted in figure 1.2.

Figure 1.2: One recorded geomagnetic disturbance-event where the GIC amplitude is plotted as a function of time. Figure adapted from [3]. © IEEE.

As seen in figure 1.2 the GIC current amplitude varies over time but with very low frequency. In this thesis, however, the GIC is considered a true DC.
1.3 The effects of GICs on a power transformer

For neutral-grounded, wye-connected transformers the GIC will pass through the windings of the transformer. The DC current will magnetize the transformer core, giving rise to a DC offset in the flux density of the core. This leads to increased reactive power losses, saturation of the core \cite{4}, and heating of the windings and structural parts \cite{5}. Other effects of GICs in a power transformer include tripping of relays and gassing \cite{2}.

If the rated voltage is applied to the terminals, while a DC current is passed through the windings, the core will saturate during one half of the period. This is called half-cycle saturation and the behavior is illustrated below.

![Figure 1.3: This figure illustrates half-cycle saturation of the core. Upper left shows the flux density, upper right the non-linear B-H relation of the core and lower right is the magnetization current. Figure adapted from \cite{4}.](image)

A further illustration of the phase currents and the limb flux density for specific DC currents injected into in the neutral is shown below.
Figure 1.4: Limb flux density when a transformer is subjected to a DC current in the neutral. A DC offset in the flux density can be seen, illustrated by the dotted lines. The limb flux density is plotted for one period.

Figure 1.5: Phase currents for different DC currents in the neutral. The phase current is plotted for one period. When the core is saturated, the current will increase significantly.

There are two things to consider here. First, the DC current will generate a DC flux that has to close the magnetic loop somehow. Second, the current spikes will generate an AC flux that also has to close the magnetic loop somehow.
1.4 Objectives

A real, non-ideal transformer is a very complex unit and analysis of every part of it is outside the scope of this thesis. Instead, the parts that are relevant for understanding the behavior during GIC events and modelling of the tank are described in detail and used for further analysis.

Prior to this thesis, a simplified, frequency independent tank model was used by ABB for GIC simulations.

Up until now, a few models valid for zero-sequence currents have been proposed [6] and one for GIC [7]. During the course of this thesis, a slightly different approach than what is found in [7] is to be modeled, implemented and evaluated.

The objective of this thesis is to improve the power transformer duality model used for GIC simulations at ABB, for a T-core transformer. The main aim is to improve the transformer tank model and the coupling paths to it. The improved model has to allow currents in the tank.

Due to the absence of real measurements to compare the models to, zero-sequence impedance measurements will be used to validate the model to some extent. However, the models implemented are not expected to be in perfect agreement with the zero-sequence impedance measurements.

At last, the power dissipation in the tank is to be evaluated for simulated GIC events.
Chapter 2

Theoretical framework

2.1 Three-phase transformer operation principles

This section describes the principle of operation for two common core types, the T and TY cores.

There are many different possible core configurations for a given transformer rating. For large three-phase power transformers the most common core configuration is three wound limbs with return limbs. This core configuration is called TY. TY is a Swedish abbreviation where T stands for Tre (three), meaning three wound limbs, and Y stands for Ytterben (return limbs). Another core type is the T-type. The T-type core has three wound limbs and no return limbs.

For a balanced three-phase situation, the vector sum of the applied voltages is zero. In practice this means that the magnetic loops in the core for one phase are balanced by the other phases, thus eliminating the need for return limbs. However, TY cores, i.e. with return limbs, are used in many cases to lower the height of the transformer. Return limbs takes some of the load off the yokes, thus enabling a reduction of the the cross-sectional area of the yoke while still operating the transformer at a certain flux density. An illustration of the core types is given in figure 2.1.

Figure 2.1: This figure shows an illustration of the T- and TY-type core configurations.

For GIC purposes, there is a key difference between the T- and TY core types. For a T-core, all DC flux is forced off-core, whereas the TY-core has return limbs which can be used for the DC flux. In the beginning of this thesis, it was decided that the T-core should be the
Transformers work by the principle of induction. Two or more windings are linked by a mutual flux through the core. The linked flux in the core is entirely determined by the applied voltage, given a frequency and number of turns \[S\]. The applied voltage induces an electromotive force (emf).

\[ e_1 = N_1 \frac{d\phi_m}{dt} \]  

(2.1)

Here, \( e_1 \) is the induced electromotive force, \( N_1 \) the number of turns and \( \phi_m \) is the mutual flux.

An emf is induced in the secondary winding due to the change of mutual flux.

\[ e_2 = N_2 \frac{d\phi_m}{dt} \]  

(2.2)

If the resistance in the windings is assumed to be zero, \( e_1 = U_1 \) and \( e_2 = U_2 \), where \( U_{1,2} \) are the terminal voltages.

Furthermore, the flux density is calculated by dividing the flux with the cross-sectional area of the magnetic material.

\[ B_m = \frac{\phi_m}{A_m} \]  

(2.3)

Here, \( B_m \) is the flux density and \( A_m \) is the cross-sectional area.

One limitation for transformer cores is the flux density. The magnetic material is useful up to a certain flux density, and at flux densities higher than that the current will increase a lot which in turn increase losses.

This describes the basic principle of operation of the power transformer.

### 2.2 Effect of unidirectional flux

Unidirectional flux refers to flux with the same direction coming from all three phases. Zero-sequence currents and DC currents passed through the windings both result in an unidirectional flux in the core.

A zero-sequence current means that the current phasors in all phases have the same direction. If a DC-current is injected into the neutral, it will split up between the phases where one part of the DC current will pass through each winding.
Both DC- and zero-sequence currents can produce an unidirectional flux in the core. For T-type core transformers there is no return path for unidirectional flux in the core, in contrast to the case where the core has return limbs. As a consequence, the flux is forced off-core. The transformer tank has a permeability much higher than that of oil. Thus, most of the off-core flux will close the loop through the transformer tank, until the tank is saturated.

![Figure 2.2:](image-url) This figure shows an illustration of AC and DC flux inside and outside of the core, in a T-core configuration, when the windings are subjected to a DC current. The black arrows correspond to AC flux and the red arrows correspond to DC flux. At the time instant of the figure, the inner (middle) phase will be saturated, given that the DC current is sufficiently large.

According to Faraday’s law of induction, a current will also be induced in the tank when the time derivative of the flux is not zero. It can be described as the basic transformer principle discussed earlier, but in this case a small portion of the tank will act as the secondary winding. For zero-sequence currents, the induced current will circulate around the tank perimeter. For over-excitation of the core, the current will rather be a local circulating current. Thus, the current paths in the tank will differ depending on whether the transformer is subjected to a GIC or a zero-sequence current.

### 2.3 Magnetic properties of the tank walls

A B-H curve is a curve that relates the flux density to the magnetic field inside a material.

The B-H relation of a non-linear material, such as the core- and tank steel, is characterized by its coercive field, remanent flux density and other shape parameters. The coercive field is the magnetic H-field the material can withstand without demagnetizing and the remanence is the remaining magnetization when the magnetic H-field is removed.

In order to mimic how a transformer behaves during a GIC event, a non-linear magnetic tank wall model is implemented where the magnetic parameters are fitted to actual measurements of the constructional steel used in the tank walls.
In the B-H curve, we can see how high magnetic field is required to obtain a certain flux density in the material. When the flux density crosses the knee-point of the B-H curve, the material starts to saturate. Above this point, the magnetic field required to increase the flux density more increases drastically.

In a core on the other hand, the flux density is determined by the applied voltage. When the voltage is too high, the core will saturate, and large current spikes will be seen as a result.

The B-H curve for a common tank steel, as implemented in the circuit simulation software, is seen in [Fig. 2.3](#).

![B-H curve for tank steel](image)

**Figure 2.3:** This figure shows the B-H curve for a common tank steel used in this thesis.

For the purpose of illustration, the voltage applied to produce the B-H curve in figure [2.3](#) was ramped, producing many minor loops that eventually, when the voltage was high enough, followed the major loop.

### 2.4 Modeling of magnetic circuits

To establish the layout of a magnetic circuit, the major flux paths are first identified. From the magnetic circuit, an electrical equivalent circuit model can be found that can be used in ordinary circuit simulation software. This section briefly describes the theoretical background of the magnetic circuit.

A magnetic reluctance model is essentially a circuit model where magnetomotive force $F$ and magnetic flux $\phi$ are modeled instead of electric voltage and current. Magnetic reluctance is analogous to electric resistance and is calculated in a similar manner. In other words, the reluctance $R$ is defined as the magnetomotive force $F$ divided by the magnetic flux $\phi$.

$$R = \frac{F}{\phi}$$ (2.4)
It is sometimes useful to calculate the reluctance using material parameters, as seen in equation (2.5).

\[ R = \frac{l_{\text{mag}}}{\mu A}. \] (2.5)

Here, \( l_{\text{mag}} \) is the magnetic path length, \( \mu \) is the permeability of the material and \( A \) is the magnetic cross-sectional area.

One advantage of magnetic circuits is that they are straightforward in terms of relating the magnetic circuit model to the physical system’s geometry.

However, for non-linear materials, the use of magnetic circuits becomes approximative since the coupling paths change depending on the current state of the material. The largest limitation of this method lies herein.

### 2.5 Lumped element modeling

Lumped elements refer to a method of discretizing physical quantities in a space into lumped elements. A lumped element is a component that corresponds to a specific geometrical area wherein the quantity modeled is assumed constant.

The lumped element approach is used to simplify simulation and calculation of different quantities. The purpose of the lumped element model is to reduce the number of state variables while still providing a satisfactory description of a system [9].

When determining the number of lumped elements to divide a space into, it is necessary to take into account the real distribution of the modeled quantity inside the space. For instance, a magnetic sheet subjected to a time-varying magnetic field will have an exponential-like distribution of the flux inside the sheet. It is known as the penetration of an electromagnetic wave.

The skin depth is defined as the depth of the material where the amplitude of the wave has decreased to 1/e of the incoming wave amplitude. The skin depth can be calculated using equation (2.6).

\[ d_s = \sqrt{\frac{\rho}{\pi f \mu_r \mu_0}} \] (2.6)

Here, \( d_s \) is the skin depth, \( \rho \) is the resistivity of the material, \( f \) the frequency of the wave, \( \mu_r \) is the relative permeability of the material and \( \mu_0 \) is the permeability of free space. In equation (2.6), \( \mu_r \) is usually considered constant. However, when the material is saturated, \( \mu_r \) decreases. This means that the penetration depth will also be a function of the flux density in the magnetic material.

Instead of modeling the transformer mathematically, it is represented with a circuit model that can be used to simulate certain operating conditions.

The tank walls are divided into a number of parallel elements. Each element is represented with one or a few lumped components and the flux density, for instance, in the lumped component is assumed to be the same as the flux density in that element of the tank wall.
Figure 2.4: Division of the tank wall into two lumped components. Two elements are far too few, as the flux distribution approximation is far too coarse. The two inductors correspond to the electrical equivalent of the magnetic circuit.

When determining the number of elements to divide a space or component into, it has to be considered what the model will be used for. For instance, for the tank walls, a higher frequency will mean that the penetration depth is less, thus requiring more elements. Fewer elements will reduce computational effort while reducing the accuracy of the model. Thus, there will always be a trade-off between computational effort and degree of accuracy.
2.6 Duality between magnetic and electrical circuits

In order to simulate the magnetic circuit using circuit simulation software, it is necessary to find the electrical equivalent circuit for a given magnetic circuit. In this section, the duality between interlinked electrical and magnetic quantities is described and the concept of magnetic inductance is introduced.

For a planar magnetic circuit an electrical equivalent, which is dual to the magnetic circuit, can be found [10], [11].

A planar magnetic circuit means that no wires in the circuit are crossing each other, i.e. the circuit is two dimensional.

The magnetic circuit is transformed into its dual electrical circuit by setting up a "dual mesh" [10], where all loops become nodes, all nodes become loops, all series connections become parallel connections and all parallel connections become series connections. For larger reluctance circuits, this proves to be a time consuming task and the method is described more thoroughly in [10] and [11].

The duality principle can be illustrated by the winding component [9] as seen in section 2.6.1, where one side of the circuit is magnetic and the other side is electric.

For the electrical equivalent circuit, the voltage is dual to the time derivative of the flux $\frac{d\phi}{dt}$.

$$u \iff \frac{d\phi}{dt}$$

(2.7)

The current is dual to the magnetomotive force $F$.

$$i \iff F$$

(2.8)

The dual of a reluctance is an inductance.

$$\mathcal{R} \iff \frac{1}{L}$$

(2.9)

For a non-linear material, the reluctance, and its dual inductance, will of course also be non-linear. The non-linearity can be modeled in many ways, one way being the Jiles-Atherton model. The circuit simulation software used, MicroCap, implements a Jiles-Atherton model for non-linear materials.

For a Jiles-Atherton model, the material is parametrized by the steepness of the B-H curve (parameter A), hysteresis (parameter K), saturation (parameter MS) and other parameters.

2.6.1 Modeling of induced eddy currents

In this section, an approach to modeling induced currents in a material is explained and illustrated with the winding component.

Consider flux entering a magnetic material, perpendicular to the surface of the sheet, where the conductivity of the material $\sigma \neq 0$ and the time derivative of the flux density $\frac{dB}{dt} \neq 0$. According to Faraday’s law of induction, a current will be induced, ultimately counteracting the change of flux. It is possible to formulate the linked flux- and current distribution mathematically using Faraday’s law and Ampere’s law.
\[ \nabla \times \mathbf{H} = \mathbf{J} \quad (2.10) \]
\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2.11) \]

In equation (2.10), the displacement field \( \mathbf{D} \) is omitted.

There are many ways to solve the equations above, FEM simulations being the most effective and practical way for a complex 3D arrangement such as the power transformer.

While the actual induced current is a three-dimensional quantity, we can discretize it by assuming a current path- and area thus reducing the problem to a simple electrical circuit. This, of course, introduces some limitations to the model. However, if we can provide a satisfactory description of the system for a specific operating condition using an electrical circuit, it will greatly reduce computational effort and time needed to simulate a specific event.

The induced current in a magnetic material can be viewed as a simple transformer circuit depicted in figure 2.5 [12], also known as the winding component. In the winding component, the magnetic side is on the left and the electrical side is on the right.

![Figure 2.5: This figure shows the winding component, for induced current in a magnetic material. \( \mathcal{F} \) is the magnetomotive force, \( \varepsilon \) is the induced emf and \( R_{\text{eff}} \) is the effective resistance of the current path. The magnetic side is on the left and the electrical side is on the right. Figure adapted from [12].](image)

Basic circuit theory can be applied to the circuit in figure 2.5 as seen in equations (2.12)-(2.14). In this case \( N=1 \).

\[ \varepsilon = -N \frac{d\phi}{dt} \quad (2.12) \]
\[ I = -\frac{N}{R_{\text{eff}}} \frac{d\phi}{dt} \quad (2.13) \]
\[ \mathcal{F} = NI = -\frac{N^2}{R_{\text{eff}}} \frac{d\phi}{dt} = -\frac{1}{R_{\text{eff}}} \frac{d\phi}{dt} \quad (2.14) \]

The right hand side in equation (2.14) can be identified as a "magnetic inductor" where the inductance is \( 1/R_{\text{eff}} \). Thus, induced currents resulting in a counteracting flux can be represented with an inductor in the magnetic circuit with an inductance equal to \( 1/R_{\text{eff}} \) [12].

For a magnetic inductance, its dual is simply the inverse of the effective resistance of the current path, as seen above.

\[ \mathcal{L} \leftrightarrow \frac{1}{R} \quad (2.15) \]
Here, $L$ denotes the magnetic inductance. The magnetic inductance is used in the magnetic circuit to model induced currents.

### 2.7 Modeling of GIC currents

This section describes how to properly model the transformer behavior during a GIC event. Not only the transformer needs to be modeled, but the GIC current and the grounding of the transformer also have to be represented.

A GIC current is caused by changes in geomagnetic flux linking the power system, driving a current through the neutral as shown in figure 1.1.

In the electrical equivalent circuit, the GIC current is modeled as a voltage source in series with a resistance, connected between the neutral and ground. The sources for feeding the transformer circuit and the GIC current model are illustrated in figure 2.6.

Figure 2.6: This figure shows the GIC current modeling and the voltage sources energizing the transformer. Sources $U_a$, $U_b$ and $U_c$ are used to energize the transformer. The DC-source $U_{DC}$ and resistor $R_{\text{ground}}$ comprises the modeling of a GIC current. $T_a$, $T_b$ and $T_c$ correspond to phases a, b and c on the transformer model.

The voltage $U_{DC}$ is set so that $U_{DC} = I_{\text{GIC}} \cdot R_{\text{ground}}$ where $I_{\text{GIC}}$ is the desired GIC current to be used. This model also allows the time constant for the circuit to be adjusted to speed up simulations.

The time constant for an LR circuit is determined by the ratio $L/R$. For power transformers, $L$ is very large, ranging from a few to a few hundred henry for an unloaded transformer, depending on the frequency. $R$ is in the order of ten to a few hundred milliohms. The ratio between the two means that the time constants are very long. For GIC currents, the simulations must be carried out in transient mode. This means that the calculations must be performed in the time domain, implying very long simulation times for long time constants. However, by increasing the grounding resistance $R_{\text{ground}}$ and adjusting the voltage $U_{DC}$ accordingly, the
simulations can be sped up significantly while subjecting the transformer to the same GIC current.

In this thesis, the transformer is modeled for a no-load situation, implying that the grid properties are omitted.
Chapter 3

Evaluation of flux and current distribution inside the transformer

In this chapter, FEM simulations are performed to create an understanding of the tank behavior and the magnetic coupling to the tank.

3.1 Unit used for simulations

There were many constraints for the unit that was to be used as a reference unit. In the beginning of this thesis, the following requirements were determined:

- Transformer type: Three phase, three limb power transformer (T-core)
- Data: Zero-sequence impedance measurements have to be available
- Data: Measurements of losses for zero-sequence currents have to be available

After reviewing a large number of test reports, a 226 kV, 200 MVA T-core transformer was chosen. The unit is specified for 50 Hz. The test report for this unit provided both zero-sequence impedance measurements as well as losses for zero-sequence currents. These measurements are meant to serve as a form of verification of the models later developed.

The transformer is YN/yn/d(internal)-connected with a tertiary winding that can be opened from the outside. YN/yn means that both primary and secondary are Y-connected with neutral point. D internal means that there is a delta-connected tertiary winding. It is an important aspect that the tertiary winding can be opened for the sake of verifying the model. A delta-connected tertiary will act as a stabilizing winding by providing a path for third-harmonic currents. Unless it is opened, it will influence the transformer behavior in the same way as the tank, thus complicating the task of separating the influence of the tank.

This unit will be referred to as Unit 1.

1Further details are not provided due to ABB Power Transformers Non-Disclosure Policy.
3.2 2D FEM simulations

In this section, FEM simulations are performed for a simplified 2D axisymmetric model of one of the outer phases of the transformer. The results are meant to assist in determining the numerical values of the lumped components. The purpose of the simulations is to determine approximate areas and lengths of magnetic coupling paths through the transformer oil to the transformer tank.

For the 2D simulations, a few simplifications are made:

- The boundary condition for the tank boundary is set so that it attracts magnetic flux. It corresponds to the tank having a permeable material.
- The winding is fed with a DC current.
- The boundary condition at the symmetry line, i.e. $x = 0$, is that the vector potential $A$ is zero. This corresponds to a flux only having one direction at the symmetry line.

The following simulations are performed in Ace TripleC. In a real transformer, a tap changer is usually mounted between one short side of the tank and the core. For this reason, simulations are performed for both sides of the core since the radial gaps to the tank are different depending on the side. The two sides are both taken into account in the effective tank radius described later.
Figure 3.1: Axisymmetric 2D FEM simulation of the gap between core and tank, side with tap changer. The lines are flux lines.
Figure 3.2: Axisymmetric 2D FEM simulation of the gap between core and tank, side without tap changer. The lines are flux lines.

It can be seen in figures 3.1 and 3.2 that the flux enters the tank cover in a concentrated manner with an area approximately equal to the core area. It can also be seen that the flux enters the tank radially. The height of the radial magnetic coupling path can be assumed to be approximately half of the limb height.
Figure 3.3: Zoom on the axial gap core-tank cover on figure 3.2. The lines are flux lines.
3.3 3D FEM simulations

The following simulations are performed in order to visualize the induced currents in the transformer tank. The simulations are performed in Infolytica MagNet.

During a GIC event, the windings will be subjected to a near-DC current. Due to small variations in the external magnetic field, the current induced will not be a true DC current but rather a near-DC current. However, in this thesis, a GIC event is modeled as a true DC current in the neutral. This will result in the core being excited by the DC current. It can be seen as having a DC offset to the flux density in the core. This means that when the DC current is over a certain limit, the core is driven into saturation during less than 90 electrical degrees. As a consequence, large current spikes can be seen in the phase currents when the core is saturated. The current spikes generate flux that is forced to close the loop outside the core since the core has no return limbs.

In the model used, the winding resistance was turned backwards and thus the current has another direction than the flux, as seen in figures 1.4 and 1.5.

While FEM simulations are rather efficient for solving time harmonic states, solving transients takes a lot of time. For time harmonic states, the problem can be solved in the frequency domain whereas transients must be solved in the time domain. Moreover, power transformers have very long time constants and it would probably take days, if not weeks, to solve a transient until the transformer has reached steady state. For this reason, simulations of tank behavior are performed for over-excitation of the core, so that it can be solved with a time harmonic solver. Over-exciting the core means that the limbs are saturated one phase at a time like during a GIC event, however it will include saturation both at the positive and negative part of the cycle. Over-excitation of the core is assumed to yield current paths in the tank comparable to the current paths if the transformer was subjected to a real GIC current.

Simulations were also performed for zero-sequence currents to illustrate the tank behavior for such events. When passing a zero-sequence current through the windings of a T-core transformer, the generated flux is forced to close the loop outside the core. This is due to the absence of return limbs. Since the tank has a permeability much higher than that of oil, the flux will close the loop mainly through the tank until the tank reaches saturation. After saturation, the axial oil gap between winding and tank will become more important.

The tank walls are modeled using surface impedance boundary conditions and the core material is isotropic. An isotropic magnetic material means that the permeability is the same for any direction, whereas a real core uses an anisotropic material. Using an anisotropic core material in the simulations increases the computational effort and decreases stability of the model.

The model used is a simplified model of the transformer but it is considered sufficient for the purpose.

3.3.1 Over-excitation

The simulations below are performed for the geometry of the unit described in section 3.1. In the simulation results the current density, flux density and direction of the current on the
inside of the tank wall and cover are shown. The core, windings and other parts of the power transformer are not shown. The applied voltage is 50 % higher than rated voltage to achieve over-excitation of the core. In MagNet, it is only possible to evaluate the results at 0 and 90 electrical degrees, so the results have to be handled with great care.

The applied voltage is seen in figure 3.4.

Figure 3.4: Applied voltage for the simulations. The line marks 90 electrical degrees.

From the figure it is seen that at 0 electrical degrees, phases B and C will be saturated, and at 90 electrical degrees, only phase A is saturated.
Figure 3.5: Flux density (shaded plot) and current direction (arrows) during over-excitation at 0 electrical degrees. The tank is tilted so that it is seen from below and left.

Figure 3.6: Current density (shaded plot) and current direction (arrows) during over-excitation at 0 electrical degrees. The tank is tilted so that it is seen from below and left.

From figure 3.6 it is apparent that the current density has some peaks. The peaks can be caused by two things. First, a high flux density entering the tank, meaning a strong magnetic coupling, in combination with a time-varying field will increase the local current
density. Second, if the induced currents from flux entering and exiting the tank, for instance, have the same direction in some area the current density will also be higher.

A simplified overview of the saturated limbs and induced current patterns for 0 electrical degrees is depicted in figure 3.7.

Figure 3.7: This figure illustrates the induced current patterns in the tank when phases B and C are saturated. The yellow color indicates saturation of the limb.
For 90 electrical degrees, only phase A is saturated according to figure 3.4.

A simplified induced current pattern illustration, for 90 electrical degrees, is depicted in figure 3.10.
While over-excitation saturates the limbs at both the positive and negative parts of the cycle, a DC excited core will only saturate during one half of the cycle. Thus, the induced current patterns have to be separated to account for the currents induced by each phase, in the tank, in order to discretize the model later.

The FEM simulations above also show that the off-core flux uses a part of the tank rather than the whole tank as a return path, when one limb is saturated at a time.
3.3.2 Zero-sequence

For zero-sequence currents, FEM simulations are performed for Unit 1. The simulations are performed to establish the circulating current pattern when the transformer is subjected to a zero-sequence current.

Figure 3.11: Current density (shaded plot) and current direction (arrows) when passing a zero-sequence current through the windings, at 0 electrical degrees. The tank is tilted so that it is seen from below and left.
In this case, the current path can be assumed to be concentrated to a central belt of the tank walls. The height of the current belt can be assumed to be half of the tank height. This phenomenon is well known and zero-sequence current being passed through the windings have been observed to result in burnt paint on the tank walls.

From the simulations it can also be seen that the flux distributes evenly along the tank perimeter, for zero-sequence currents.
Chapter 4

Models and parameters

4.1 Transformer tank models

Three different tank models were implemented and evaluated in this thesis. They are also compared to the previous tank model used by ABB.

In the first model, a tank model common for all phases will be evaluated. This model was developed as a zero-sequence model and will be used for comparison. This model was first suggested by Zirka et al. in [6] and it merges the tank flux from all three phases into one tank flux that enters the tank walls. This model is characterized by the tank being a common flux path for all phases, and is therefore called the common tank. The layout of this model also implies that the currents induced in the tank, from each phase, have the same direction.

During a GIC event, the core limbs will saturate one phase at a time. High currents will introduce more flux that cannot close the loop through the core, meaning that the flux will use other paths to return. Most of the flux will, until saturation of the tank, use the section of the tank in proximity to the winding to close the loop. For this reason, the tank has to be divided magnetically into one tank part per phase. This assumption leads to the models that have been developed during the course of this thesis.

The second model is an improvement of the current model used today at ABB. The previous model did not allow currents in the tank whereas the new models do. The previous tank model consists of one non-linear magnetic tank wall element per phase without any current path. The advantage of this model is that it is divided per phase magnetically, and is therefore called the ”Per-phase tank”.

The third model implemented is a further improvement of the per-phase tank and is a combination of the common tank and per-phase tank. It is divided per-phase magnetically and it allows local currents in the tank walls. It also takes the fictive winding action, that the tank provides in a real transformer, into account. Furthermore, the tank cover and tank walls are separated.

All three tank models above allow currents in the tank which was not the case prior to this thesis. They also divide the tank thickness into a number of layers to account for the gradual saturation of the tank wall, which was not the case prior to this thesis. The final proposed tank wall model will provide a possibility to approximate the tank wall and tank cover losses
using circuit simulation software. The parameters for the proposed model will be calculated using a simple Excel sheet where the mechanical and electrical dimensions of the transformer are inserted and the output can be pasted into the circuit simulation software, MicroCap.

In the following chapter, the background of the tank models is first described. Then, the different approaches are shown. At last, an overview of the other lumped components used for simulations is shown.

4.2 Major flux paths

Consider a three-limb, three-phase transformer without side limbs (T-core) and with 6 windings. The major flux paths are determined according to figure 4.1.

![Figure 4.1: Major flux paths for one phase for a T-core transformer. Here, A and B are the air cores, the ducts between the windings, C is the core, D is the axial path core-tank cover, E is the radial path core to tank, F is the axial oil return path, G is the transformer tank, H is the yoke, and I is the tank cover and bottom.](image)

4.3 Non-linear magnetic material implementation

The non-linear inductances used in the circuit simulation software MicroCap are parameterized by a few parameters. First, the magnetic path length must be set. The magnetic path length is simply the length of the magnetic path in the direction of propagation.

Then, the magnetic path cross sectional area must be set. It is simply the magnetic cross sectional area in the direction of propagation.

At last, the magnetic properties of the material must be set. In MicroCap, a Jiles- Atherton non-linear model is used. The parameters used for fitting the B-H curve are curve steepness (A), hysteresis (K) and saturation (MS). The model used in MicroCap is fitted to actual measurements of the steel used in the transformer tank.
It was seen in [6] that the hysteretic properties of the tank influence the tank behavior at lower degrees of saturation of the tank wall. The results indicate a lower contribution to the inductive part of the tank, for a hysteretic tank material, at low degrees of saturation of the tank wall.

This reasoning is validated by considering the inductance of the tank to be proportional to the relative permeability of the material. A hysteretic material will show a lower permeability than a non-hysteretic material at lower flux densities and for this reason the hysteretic properties were included in the tank model.

The fitted model output is seen in figure 4.2 and the measurements of one common tank steel is seen in figure 4.3. In the model output, the first minor loops have been excluded for a better comparison to the measurements.

![Figure 4.2: B-H curve for the fitted model of the transformer tank.](image1)

![Figure 4.3: B-H curve from measurements of a common tank steel.](image2)

As seen in the figures, the model does not perfectly reproduce the measurements, however it is deemed sufficient.
4.4 Transformer tank modeling

4.4.1 General tank modeling

The tank walls are divided thickness-wise into $n$ elements. A coordinate system is introduced in the tank walls according to figure 4.4.

![Tank wall field distribution](image)

**Figure 4.4:** Tank wall field distribution. Figure adapted from [6].

When modeling the tank walls, it is first necessary to determine what is to be modeled. Based on 3D FEM simulations performed by ABB prior to this thesis, it is decided that the currents induced by flux entering the tank perpendicular to the surface of the tank are to be modeled.

The modeling approach for positive-sequence over-excitation follows below. The modeling approach described here does not apply to the zero-sequence model used later for comparison.

For one layer of the tank wall, the modeling is illustrated in figure 4.5.
Figure 4.5: This figure illustrates the modeling, for one layer, of the tank walls and cover/bottom. Blue lines correspond to flux and the black circle corresponds to an induced current. \( \phi_1 \) is the incoming flux, \( \phi_2 \) is the flux that uses that layer to close the magnetic loop and \( \phi_3 \) is the flux that penetrates deeper into the tank wall, i.e. to the next layer. A further illustration is seen in 4.6. In reality, \( \phi_{1,3} \) and \( \phi_2 \) are not perpendicular, and this figure serves only to illustrate the modeling.

From figure 4.5 it is possible to determine the layout of the magnetic circuit.

Figure 4.6: This figure shows the magnetic circuit for the tank wall and tank cover/bottom. The flux quantities refer to the ones defined in figure 4.5. Note that the component R corresponds to magnetic reluctance and L to magnetic inductance, as described earlier.

From figure 4.6 it is possible to find the electrical equivalent circuit of the magnetic tank wall circuit by means of the duality principle.
Figure 4.7: This figure shows the electrical equivalent circuit for the tank wall and tank cover/bottom found using the duality principle. This circuit is referred to as a ladder circuit (LC). Note that the components in this circuit are electrical components but their numerical values are calculated from the magnetic quantities in figure 4.6.

As seen above, the tank wall portions are modeled using ordinary Cauer circuits. Cauer circuits are usually used for modeling magnetic sheets. However, for a magnetic sheet, the flux and current paths are defined differently.

For the tank walls, each magnetic element of the tank wall will be represented by an inductance in the electrical equivalent and the currents induced will be represented by the current passing through resistors.
4.4.2 Common tank model

The common tank model is a zero-sequence model for the power transformer that takes into account the influence of the tank walls.

This model is proposed in [6] and is used for comparison.

It is important to note that in this approach the tank walls are modeled in a different manner than what is described in section 4.4. An illustration of the tank wall modeling for the common tank is seen in figure 4.8. The reader is referred to [6] for a complete description of this model. In summary, the common tank approach assumes that all tank flux distributes evenly along the tank perimeter, and that the induced currents in the tank are concentrated to a central belt of the tank wall.

![Figure 4.8](image)

**Figure 4.8:** This figure shows the assumed tank flux- and current paths used in the common tank approach. Figure adapted from [6].

From figure 4.1 a reluctance circuit is set up according to figure 4.9 where each path marked with letters A-H have a corresponding reluctance. The tank cover is omitted in this approach.

![Figure 4.9](image)

**Figure 4.9:** Reluctance circuit of the T-core transformer. The shaded reluctances are non-linear and the unshaded are linear reluctances. Each reluctance represents the magnetic resistance for the corresponding flux path.
Based on the duality principle, the circuit described in figure 4.9 is transformed to its dual electrical circuit seen in figure 4.9. For the non-linear magnetic paths, path lengths and path areas are approximated. The non-linear elements use BH-characteristics fitted to the actual materials used. For the linear inductances, the inductance is approximated using analytical expressions and assumptions based on FEM simulations. The approximation of oil-path inductances will be further discussed later.

The electrical equivalent circuit seen in figure 4.10 is used and the inductance $G$ is replaced with a ladder circuit with a number of layers. However, the actual number used is not provided in this report. In [6], 25 layers are used to achieve a smooth flux distribution.

The number of layers of the tank walls have an impact on the performance of the circuit. For the common tank model, the losses and impedance of the circuit were compared for different number of layers, as seen in figure 4.11.

![Figure 4.10: Duality derived electrical equivalent circuit for the common tank. All inductors have $N_{\text{ref}}$ turns and their inductances are determined by means of approximation of magnetic resistance for the corresponding path. $N_b$ is the number of turns on the HV winding and $N_a$ is the number of turns on the LV winding.](image)

![Figure 4.11: Losses when applying a zero-sequence voltage and zero-sequence impedance as a function of number of layers in the ladder circuit.](image)

What can be seen is that both losses and impedance reaches its asymptotic value when a
certain number of layers are used. The layer thickness roughly corresponds to the penetration depth, or less, when losses and zero-sequence impedance are close to their asymptotic value.

4.4.3 Per-phase tank model

Due to the uneven distribution of the flux along the tank perimeter, it is necessary to separate the magnetic tank wall elements for each phase. An illustration of the division of the magnetic tank parts is depicted in figure 4.12. In this approach, the tank cover is omitted and the tank walls in proximity to the winding are divided into a number of elements. The elements are considered to be parallel magnetic paths with associated losses. A reluctance circuit is set up according to figure 4.13.

![Figure 4.12: This figure shows an illustration of how the tank is divided magnetically.](image-url)
Figure 4.13: This figure shows the magnetic circuit of the per-phase approach. The electrical side, i.e. the path for circulating current, is not included in this diagram to make the circuit easier to interpret and keep the circuit strictly magnetic.

With the tank walls being separated per phase, the effective cross-section area for the magnetic path must be approximated. The area is approximated using FEM simulations. The effective cross-sectional magnetic tank area is assumed to be 50% larger for the outermost phases.

The electrical equivalent circuit is found for the reluctance circuit seen in figure 4.13. The electrical equivalent circuit is seen in figure 4.14.

Figure 4.14: Duality derived electrical equivalent circuit for the per-phase tank. All inductors have \( N_{\text{ref}} \) turns and their inductances are determined by means of approximation of magnetic resistance for the corresponding path. \( N_b \) is the number of turns on the HV winding and \( N_a \) is the number of turns on the LV winding.

The tank, G in figure 4.14, is modeled by means of ladder circuits to account for the non-linear tank walls and the induced currents from flux entering the tank perpendicular to the surface of the tank. For the per-phase tank, the circuit simulation software MicroCap set the limit to how many tank wall elements could be used.

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1Further details are not provided due to ABB Power Transformers Non-Disclosure Policy.
2Further details are not provided due to ABB Power Transformers Non-Disclosure Policy.
4.4.4 Hybrid tank

The hybrid tank is a further improvement of the per-phase approach. In this approach, the cover and tank walls are separated. Thus, the axial coupling path from the core to the cover and the radial coupling path have to be separated.

An illustration of the division of the tank, magnetically, is provided in figure 4.15.

**Figure 4.15:** Illustration of how the tank is divided magnetically in the hybrid tank approach. Darker color indicates cover or bottom of the tank.

A reluctance model is set up according to figure 4.16.

**Figure 4.16:** Reluctance model for the hybrid tank approach

The separation of the tank also implies that the earlier global circulating currents, depicted
in figures 3.7 and 3.10 have to be divided further. Local circulating current patterns are assumed in the tank walls and tank cover.

From the local circulating current patterns, separate models for tank wall and cover are made and implemented using ladder circuits. The resistances of each layer in the ladder circuits correspond to the effective resistance seen by the induced current. The resistances as well as all other components are referred to the number of reference turns in the electrical equivalent circuit. For the outer phases, the effective length of the current path will include both one short side of the tank wall and the corresponding portion of the long side of the tank wall.

The dual circuit for the reluctance circuit seen in figure 4.16 is found and it is seen in figure 4.17.

Figure 4.17: Duality derived electrical equivalent circuit for the hybrid tank. All inductors have N_{ref} turns and their inductances are determined by means of approximation of magnetic resistance for the corresponding path. N_b is the number of turns on the HV winding and N_a is the number of turns on the LV winding. LC denotes a ladder circuit.

In this approach, both the tank cover I and tank walls G consist of ladder circuits with non-linear inductances and resistors. For the hybrid tank, the circuit simulation software MicroCap set the limit to how many tank wall elements could be used.

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3Further details are not provided due to ABB Power Transformers Non-Disclosure Policy.
4.5 Lumped component approximation

In order to simulate the models above, the numerical values of the lumped components must be approximated.

For all lumped components, the inductances and resistances are referred to an arbitrarily chosen number of reference turns $N_{\text{ref}}$. Instead of calculating the magnetic resistance, i.e. reluctance, and using it as an admittance in the electrical equivalent circuit, the inductances of the lumped components are calculated directly. There is, of course, no difference between the two methods.

4.5.1 Core limbs and yokes

Each magnetic core element is represented by one inductor with $N_{\text{ref}}$ turns, with a linked saturable element. The saturable elements are parameterized by cross-sectional area, magnetic path length, and also non-linear magnetic characteristics such as steepness of the B-H curve, hysteresis and saturation. The parameters are included in the model statement for the saturable element.

The core limb and yoke inductances correspond to inductances C and H respectively in figures 4.10, 4.14 and 4.17.

4.5.2 Magnetic tank elements

The tank is divided thickness-wise, into a number of elements. Each element is represented by one inductor with $N_{\text{ref}}$ turns, with a linked saturable element. The saturable elements are parameterized by cross-sectional area, magnetic path length and non-linear magnetic characteristics. The B-H curve used for the magnetic tank wall elements is seen in figure 2.3.

The parameters are included in the model statement for the saturable element in the circuit simulation software, MicroCap.

In the electrical equivalent circuit, the tank walls and cover/bottom are modeled with ladder circuits and correspond to inductances G and I in figures 4.10, 4.14 and 4.17.

4.5.3 Oil paths

The core-tank volume is assumed to be of cylindrical shape to simplify calculations of the coupling inductances in oil. The calculations below are done so that the majority of the oil volume inside the tank is subdivided into flux tubes. A flux tube is a volume wherein the flux is assumed constant.

The calculation of the oil-path inductances are left out of this report due to ABB Power Transformers Non-Disclosure Policy, however a few simplified illustrations are provided.

First, the inductances of the oil ducts between windings and core, $L_a$, $L_b$ ("air cores") are approximated.

The air cores $L_a$ and $L_b$ correspond to inductances A and B respectively in figures 4.10, 4.14 and 4.17.

The tank steel has a permeability much higher than that of oil, in the range hundreds of times higher until saturation, and analogous to electrical current, the flux will take the path
with the least resistance. The tank, until saturation, will thus be the most dominant off-core flux path. To enter the tank, the flux has two dominant magnetic coupling paths. One is to enter the core and then pass through the axial oil gaps between top- and bottom yoke and the tank. An illustration is provided in figure 4.18.

![Diagram](image)

**Figure 4.18:** Illustration of the assumed axial coupling path to the tank for one of the outer phases. The blue arrows indicate magnetic flux.

The axial oil gap inductance $L_{\text{gap}}$ corresponds to inductance D in figures 4.10, 4.14 and 4.17.

The second most dominant return path for off-core flux are the radial paths from the core limbs to the tank. To simplify the approximation of the lumped components, an effective tank radius is assumed. An illustration of the radial coupling paths is provided in figures 4.19 and 4.20.
Figure 4.19: Radial coupling path with effective tank radius $r_{\text{tank}}$ and core radius $r_{\text{core}}$. The blue arrows indicate magnetic flux.

The outer phases are assumed to have a 270° coupling angle while the middle phase is assumed to have a 180° coupling angle, see figure 4.20. This corresponds to the inductance calculated for a coaxial arrangement being multiplied with $\frac{3}{4}$ and $\frac{1}{2}$ respectively.

Figure 4.20: This figure shows the assumed coupling angles $\alpha$ for the inner and outer phases. The coupling angle determines a factor that is multiplied with the radial coupling inductances between core and tank to improve the model.

The radial oil gap inductance $L_{\text{rad}}$ corresponds to inductance E in figures 4.10, 4.14 and 4.17.

The third most dominant flux path is the axial flux path outside the winding but inside the tank. It is of more importance when the tank is saturated. It is assumed to be an annular duct between the effective tank radius and the mean radius of the outermost winding. An
The axial inside-tank oil inductance $L_{pintank}$ corresponds to inductance F in figures 4.10, 4.14 and 4.17.

To illustrate the oil inductances described above, a 2D, side view illustration is provided for clarity.

Figure 4.21: The figure shows the axial flux path in oil. The blue area indicates the assumed flux path area.
Figure 4.22: This figure illustrates the different oil path inductances from a 2D side view. The tank cover is at the top of the figure and the tank bottom is at the bottom of the figure. The black arrows indicate the flux direction in the specific flux path, for one time instant.

As seen above certain assumptions have to be made regarding the effective dimensions\textsuperscript{4} which in turn are based on FEM simulations.

\textsuperscript{4} Further details are not provided due to ABB Power Transformers Non-Disclosure Policy
4.5.4 Induced currents

The induced currents in the tank are modeled in the magnetic circuit as a magnetic inductor, as described earlier.

When applying the principle of duality to a magnetic inductance with value $1/R_{\text{eff}}$, it has a dual that is a resistance with a value of $N_{\text{ref}}^2 R_{\text{eff}}$, referring to the reference number of turns of the electrical equivalent circuit.

For determining the numerical value of the effective resistance $R_{\text{eff}}$, equation (4.1) is used.

$$R_{\text{eff}} = \rho \frac{l_{\text{res}}}{A_{\text{res}}} \quad (4.1)$$

Here, $\rho$ is the resistivity of the tank material, $l_{\text{res}}$ is the effective current path length and $A_{\text{res}}$ is the effective current path area.

In this thesis, the current paths for each element of the tank have been approximated as disc-like paths with the same thickness as the magnetic tank elements.

The current paths and areas are approximated from 3D FEM simulations in section 3.3.

5Further details are not provided due to ABB Power Transformers Non-Disclosure Policy

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Chapter 5

Results with comments

In this chapter, the different models are compared for a number of results. The models are compared when the primary is fed with rated voltage and with secondary- and tertiary windings open.

First, the different models are compared to the measured zero-sequence impedance. Then, the models are compared for phase currents, tank losses, core peak flux density shift and the fraction of off-core flux going through oil and tank.

All comparisons are made for different DC currents injected into the neutral. All models are based on numerical values calculated using the methodology described earlier and are not adjusted to fit any measurement, thus being purely based on physical dimensions and assumptions. The reason for not adjusting the parameters is the lack of reference measurements, as there are no GIC measurements performed for the actual units.

The different models are implemented in MicroCap 11 and simulated using a computer with Intel Core i5 processor and 8 GB of RAM.

Due to ABB’s Non-Disclosure Policy, the actual simulation models are not included in this report. Instead, the reader is referred to the models presented in chapter 4.
5.1 Zero-sequence impedance and losses

As stated earlier, passing a zero-sequence current through the windings of a T-core transformer will force the flux to close the loop outside the core. This is due to the absence of return limbs. Since the tank has a permeability much higher than that of oil, the flux will close the loop mainly through the tank until the tank reaches saturation. After saturation, the axial oil gap between winding and tank will become more important.

In this section, the impedance and losses for an applied zero-sequence voltage are evaluated.

5.1.1 Zero-sequence impedance

For the unit used in this thesis, zero-sequence impedance measurements are shown in table 5.1. The test conditions for the measurements are:

- ABC-N, meaning that the primary (HV) windings are YN connected
- abcn open, meaning that the secondary (LV) windings are open
- W-W1 open, meaning that the internal delta is open

When measuring zero-sequence impedance, the unit is subjected to a zero-sequence applied voltage lower than rated voltage. The applied voltage is usually in the range 0.01-0.1 p.u., due to very high power dissipation even at low voltages. The power dissipation during the measurement may be up to a few hundred kW even at voltages as low as 0.05 p.u. For Unit 1, the measured zero-sequence impedance is found in the table below.

<table>
<thead>
<tr>
<th>U [kV]</th>
<th>Z_0/phase [Ω]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.63</td>
<td>230.4</td>
</tr>
<tr>
<td>10.17</td>
<td>234.0</td>
</tr>
<tr>
<td>8.555</td>
<td>238.5</td>
</tr>
<tr>
<td>7.424</td>
<td>242.3</td>
</tr>
<tr>
<td>6.003</td>
<td>247.5</td>
</tr>
<tr>
<td>4.138</td>
<td>255.0</td>
</tr>
<tr>
<td>2.598</td>
<td>259.6</td>
</tr>
</tbody>
</table>

Table 5.1: Zero-sequence impedance for Unit 1, from the test report. A decrease in the zero-sequence impedance is seen with a higher voltage, due to saturation of the innermost tank layers.

The zero-sequence impedance is evaluated for the different tank models and the result is found in figure 5.1.
Since the per-phase and hybrid models are not zero-sequence models, they are not expected to be in perfect agreement with the measured values of especially zero-sequence impedance. It is, however, one of the few means of verification. Also, it can be seen that the per-phase and hybrid tanks start to show the correct behavior at higher applied voltages, having the correct inclination.

When the tank reaches saturation, it is mostly the fictive winding action of the tank and the inductance of the oil gaps that determine the zero-sequence impedance. The same numerical values for the oil gap inductances are used for all four models. This means that the common tank model can be used to validate the oil gap inductances to some extent. However, due to other assumed current paths for the per-phase and hybrid tank, the zero-sequence impedance will naturally not have as good agreement with the measured values.

For the magnetically separated tank models, the zero-sequence impedance deviates more and more the lower the applied voltage. There could be many reasons for this. First, the assumed current paths of the magnetically separated models do not correspond to the actual current paths induced from an applied zero-sequence voltage, in the real transformer. For this reason, zero-sequence impedance can only tell us that the transformer is modeled somewhat correctly, since the numerical values are in the correct range. The inductance of the tank will add to the zero-sequence impedance, whereas the fictive winding action of the tank will decrease the zero-sequence impedance. The maximum of the zero-sequence impedance corresponds to the point when the tank starts reaching saturation in the innermost layers, since it by then will not add more to the inductance seen from the terminals of the transformer.

If one measured at even lower voltages than the ones presented here, a decrease in the zero-sequence impedance would be seen for the real transformer. It is possible to draw the conclusion that for an applied zero-sequence voltage, the tank saturates later than for the real case, for the models where the tank is magnetically separated per phase.
5.1.2 Zero-sequence losses

When passing a zero-sequence current through the windings, the majority of the power will be dissipated in the tank. In these results, the ohmic losses in the tank and windings are taken into account. Hysteresis losses, eddy current losses in the windings and core losses are not accounted for.

![Zero-sequence losses](image)

**Figure 5.2**: Losses when applying a zero-sequence voltage to the terminals.

**Comments**

The measured losses are in best agreement with the results from the common tank model, followed by the hybrid tank. The previous tank model shows very low losses, originating only from the ohmic losses in the windings.
5.2 GIC currents

In this section, the models described earlier are subjected to DC currents in the neutral. The simulations are performed in MicroCap and the results for each tank model are compared for four cases:

- 0 A DC in N (equivalent to no-load)
- 30 A DC in N
- 100 A DC in N
- 1000 A DC in N

All simulations are run until the transformer has reached steady-state. The results are plotted for one period after the transformer has reached steady-state. The secondary of the transformer model is kept open-circuited during the simulations.

5.2.1 Phase currents

0 A DC in N

![Phase current, 0 A DC in N](image)

**Figure 5.3:** This figure shows the phase current in one phase for 0 A injected into the neutral. 0 A injected into the neutral is equivalent to no-load.
30 A DC in N

![Phase current, 30 A DC in N](image)

**Figure 5.4:** This figure shows the phase current in one phase for 30 A DC injected into the neutral.

100 A DC in N

![Phase current, 100 A DC in N](image)

**Figure 5.5:** This figure shows the phase current in one phase for 100 A DC injected into the neutral.


**1000 A DC in N**

![Graph showing phase current](image)

**Figure 5.6:** This figure shows the phase current in one phase for 1000 A DC injected into the neutral.

**Comments**

It can be seen that when the injected DC current is 100 A, the phase currents differ a lot. When the flux is "allowed" to use the full cross-sectional area of the tank, even though only one phase is saturated, the tank path will provide a lower reluctance path as compared to the per-phase approaches. It basically provides a lower reluctance path for off-core flux. The effect is more obvious when the flux density in the core is close to the knee of the B-H curve.
5.2.2 Limb flux density

For the limb flux density, the peak flux density shift will be used to compare the models. The peak flux density shift is defined as the deviation of the peak flux density from the design peak flux density. The models will be compared for the different GIC currents stated earlier.

![Peak flux density shift](Image)

**Figure 5.7:** Peak flux density shift of the different models, as a function of DC current injected into the neutral. The peak flux density shift for the per-phase and hybrid tanks coincide, so that it looks like one curve is missing.

**Comments**

It can be seen that the common tank model lets the peak flux density increase slightly more than the other models. This effect is most probably because the common tank provides a lower reluctance path for off-core flux, forcing the flux to utilize the whole tank area, even though the limbs are saturated one at a time.

5.2.3 Tank flux density

The tank flux density for the implemented models is compared to that of the previous model to validate the models. It is also used for comparison of the implemented models.

The previous tank model is made up of one layer. In order to compare the implemented models, the mean value of the flux density in the different layers for each implemented model is used.

For DC flux the frequency is 0 Hz. For 0 Hz, the flux will penetrate the tank wall completely. Thus, using the mean value of the flux density for the different layers for comparison is acceptable for steady state. During the transient phase, i.e. before steady state, the flux will not penetrate the tank completely.

The simulations are carried out until the model has reached steady-state. The results are evaluated, for one period, after the model has reached steady state.
Figure 5.8: This figure shows the tank wall flux density for 0 A DC in N, for one period.

Figure 5.9: This figure shows the tank wall flux density for 30 A DC in N, for one period.
**Figure 5.10**: This figure shows the tank wall flux density for 100 A DC in N, for one period.

![Graph of Tank flux density, 100 A DC in N](image)

**Figure 5.11**: This figure shows the tank wall flux density for 1000 A DC in N, for one period.

![Graph of Tank flux density, 1000 A DC in N](image)

**Comments**

As the tank reaches saturation, flux will exit the tank and use the air outside the tank too in a real situation. The tank will become practically invisible for the flux when it is saturated. Flux densities of 2 T, in the steel used for the tank, is not reasonable. However, in this model, all of the flux is assumed to be contained inside outer boundaries of the transformer tank and thus the flux densities can become very high. It is also worth noting that 1000 A DC in the neutral is a very high current.

It is interesting to note that for 0, 30 and 100 A DC injected into the neutral, the AC flux in the tank using the previous model is higher than when allowing currents in the tank. This
is what we expect due to the opposing flux generated by the induced currents in the tank.

5.2.4 Power dissipation in the tank

Figure 5.12: This figure shows a comparison of the power dissipation in the tank for the different models. The power dissipation is evaluated for the four cases with DC injected in the neutral. Since the previous model does not take into account currents in the tank, naturally the losses in the tank will be zero.

Comments

The power dissipation in the tank presented here only takes into account the ohmic losses, i.e. $I^2R$. As seen above, the power dissipated in the tank is low for very high DC currents, for this particular unit. 5 kW will not increase the transformer tank temperature significantly, bearing in mind that the transformer tank weighs approximately 50 tonnes.
Chapter 6

Conclusions

Three models were implemented and compared to the previous model used, where two out of the three models were developed during the course of this thesis.

All models were simulated using MicroCap 11. This circuit simulation software used proved to be one of the big culprits during the course of this thesis. Many times, the software gave comments on why the solutions were not converging, especially when using many magnetic elements with strong non-linearity. The comments were, in many cases, impossible to interpret. For someone attempting similar research, it is worth considering other circuit simulation softwares.

As for the models, the first model, the common tank, was intended to use for zero-sequence currents. It showed the best agreements with the measured zero-sequence impedance. However, the model only allowed currents in one direction in the tank, and also showed losses significantly lower than the other two models for different DC currents in the neutral.

The per-phase tank was the first out of two models to have a tank separated magnetically for each phase. The zero-sequence impedance had fairly good agreement with the measurements, approximately ±10%. However, omitting the tank cover results in a coarse model that is somewhat unspecific, especially since the gap core-cover is much smaller than the radial gap to the tank thus providing a lower reluctance path for the flux to enter through the cover.

The hybrid tank was also separated magnetically for each phase. The zero-sequence impedance showed fairly good agreement with the measured values, approximately ±10%. Separating the axial and radial coupling paths and including the cover in the model adds detail to the model, and allows one to study the losses in tank wall and cover independently. The hybrid tank also shows higher losses than all other models when the transformer is subjected to a DC current in the neutral.

For the zero-sequence impedance, ±10% seems like a reasonable deviation since a rough reluctance model is used to simulate a complex 3D arrangement. The results indicate a fictive winding action of the tank.

The losses in steady state when injecting a DC current in the neutral were lower than anticipated. Saturation of the tank at DC currents over approximately 100 A in the neutral was not something that had not been foreseen.

For higher DC currents in the neutral, the flux density in the tank was abnormally high.
For high DC currents in the neutral, the air outside the tank must be taken into account.

Overall, the hybrid tank model is the most detailed of the models and is thus the proposed model for use by ABB. It approximates the zero-sequence impedance with fairly good accuracy and the losses for tank cover/bottom and tank walls are separated. The magnetically divided tank of the hybrid tank approach in combination with the separation of the tank cover/bottom and tank walls leads to the conclusion that the results found using this model are the most likely.

As for the power dissipated in the tank, it seems that forcing the DC flux off-core, as seen in a T-core, makes the tank less susceptible to excessive heating during a GIC event.

Overall, the biggest advantage of the circuit models compared to 3D FEM simulations is the ability to simulate the transformer in the time domain within reasonable time.
Chapter 7

Future work

This thesis only included analysis of the T-core. Other core configurations, such as the TY-core, may be more sensitive to GIC currents and should thus be evaluated. Single-phase transformers should also be evaluated. The modeling approach in this thesis should be easy to extend to other core types.

The simulations performed, when the software is working as intended, take a lot of time. It may be possible to determine expressions for the losses in the tank, for different GIC currents, based on the mechanical dimensions of the transformer. This would be a much more efficient way to evaluate the tank losses for different transformers.

A macro or similar should be developed for the electrical equivalent circuit model. The macro should take the electrical design software output and make a model from it. Today, the model parameters are calculated using an Excel sheet and then pasted into the MicroCap model.

During the course of this thesis, one attempt was made to divide the tank wall and cover height-wise. It proved to be a challenging task and the time was not sufficient to complete this approach. However, the idea of dividing magnetic elements height-wise shows some promise and should be investigated further. The same idea can probably be applied to other magnetic parts of the transformer too, such as other constructional parts.
Bibliography


